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Bidirectional AC / DC Converter with Reduced Switching Losses Using Feed Forward Control

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Abstract: ***The main objective of this project is to provide power transfer between AC grid and DERs. The proposed converter presents four switches with few switching sequence to operate either in rectifier or inverter mode and reduces the switching sequence. The number of switching's of proposed converter is one-fourth that of conventional unipolar PWM and bipolar PWM. The proposed feed-forward control is developed for better performance in rectifier mode and inverter mode. This new PWM method is preferred in renewable energy system for bidirectional power flow using single phase full bridge converter to accomplish good ac current shaping and dc voltage regulation.***

Keywords: Bidirectional AC/DC converter, Total Harmonic Distortion (THD), Feed forward control.

1. Introduction

In recent years, with increase in consumption of electricity the use of transmission system has increased predominantly which tends to increase in losses due to transmission of power from far places. So there comes the DER system where power to the localized area can be supplied from the renewable power plant which reduces transmission losses. But there is a need of a link between grid and DER when the power from DER is in excess or deficiency there come the concept of converter which is to be placed between them. The single phase AC/DC converter is widely used in these applications. AC/DC PWM converters are used as interface in a grid tied system, for providing power factor correction, low distortion line current, high quality dc output voltage and bidirectional power flow capability. Several PWM strategies have been utilized in a single phase AC/DC converter such as Bipolar Pulse Width Modulation (BPWM), Unipolar Pulse Width Modulation (UPWM), Hybrid Pulse Width Modulation (HPWM) and hysteresis switching. UPWM has a smaller ripple in the DC side current and lower AC side harmonic content compared to BPWM. The switching frequency in the AC voltage is double in UPWM. The HPWM uses two out of four switches at high frequency and utilizes the remaining switches at the low frequency to reduce the switching frequency and to achieve better quality output, but still the switching loss in the HPWM is same as that of unipolar PWM. The hysteresis switching method utilizes hysteresis in comparison with the actual voltage and current with reference. Although the hysteresis switching method has the advantages of simplicity and robustness, the converters switching frequency depends largely on the load parameters and consequently the harmonic ripples are not optimal.

To have effective utilization of the distributed energy resources (DERs) and retain power system stability the bidirectional AC/DC converter is important. The energy from the DC Bus can be easily transferred into AC grid through the bidirectional AC/DC converter when DERs have enough power; otherwise the bidirectional AC/DC converter can simultaneously and quickly change the power flow direction from AC grid to DC grid and gives enough power to the DC load and energy storage system. PWM converters are used for modular system design and system reconfiguration.

2. Proposed System

A single-phase bidirectional AC/DC converter is used as the interface between the AC grid system and DERs to maintain good dc voltage regulation and ac current shaping. The topology of the single phase bidirectional AC/DC converter is shown in fig. 2.1 this topology allows bidirectional power flow between DERs and AC grid system. In single phase bridge converter to achieve bidirectional power flow in renewable system a PWM strategy may be applied to accomplish voltage regulation in DC side and current shaping in AC side. Generally, BPWM and UPWM strategies are often utilized in a single phase AC/DC converter but now a simplified PWM strategy is proposed. This proposed simplified PWM only changes the switching status of active switch.

In these proposed simplified PWM to achieve both charging and discharging of the ac side inductor current there is change of only one active switch status in switching period. Therefore, the proposed PWM strategy reduces the switching losses and provides high conversion efficiency. The switching status of the proposed PWM is listed in Table 1 and 2 for rectifier mode and inverter mode operation, respectively. Therefore, the proposed PWM strategy reduces the switching losses and provides high conversion efficiency.

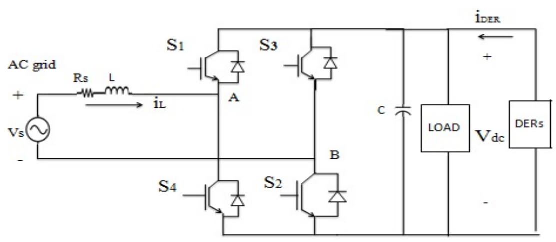

Figure 2.1: A bidirectional single-phase AC/DC converter in the renewable energy system

The switching status of the proposed PWM is listed in Table 1 and 2 for rectifier mode and inverter mode operation, respectively.

Table1: Rectifier mode switching combination

	Status	S_1	S_4	S_3	S_2	
Vs>0	A	OFF	OFF	ON	OFF	$V_L>0$
	B	OFF	ON	OFF	OFF	
	E	OFF	OFF	OFF	OFF	$V_L<0$
Vs<0	C	ON	OFF	OFF	OFF	$V_L<0$
	D	OFF	OFF	OFF	ON	
	E	OFF	OFF	OFF	OFF	$V_L>0$

Table 2: inverter mode switching combination

	status	S_1	S_4	S_3	S_2	
Vs>0	F	ON	OFF	OFF	OFF	$V_L>0$
	G	OFF	OFF	OFF	ON	
	H	ON	OFF	OFF	OFF	$V_L<0$
Vs<0	I	ON	ON	OFF	OFF	$V_L<0$
	J	OFF	OFF	ON	OFF	
	K	OFF	ON	ON	OFF	$V_L>0$

For explanation of how the proposed PWM works, consider the single phase bidirectional AC/DC converter system as shown in fig 1 and assuming that AC grid system has the internal impedance which is highly inductive which is represented by L. Considering the equivalent series resistance (ESR) of inductor is negligible.

3. Rectifier Mode

The switching combination of the proposed PWM operated in the rectifier mode is listed in Table 1. In positive half cycle of ac grid voltage source i.e. when $V_s>0$, the switching of switches is as status A and status B as listed in Table 1. In status A switch S_3 is turned on and inductor current path is V_s – L – D_{S1} – S_3 – V_s and in status B switch S_4 is turned on and inductor current path is V_s – L – S_4 – D_{S2} – V_s. Using Kirchhoff's voltage law the voltage relationship is:

$$Vs - L\frac{d}{dt}i = 0 \quad (2.1)$$

While $V_s>0$, in both status (status A and status B) the inductor current is increasing and the voltage across the inductor is V_s. Therefore in both this conditions (status A and status B) the inductor current is in charging state. In both this cases load voltage is greater than zero ($V_L>0$).

In positive half cycle when all switches are tuned off that is when the converter is in status E. In this status as all switches are turned off the inductor current takes the path of V_s – L – D_{S1} – C – D_{S3} – V_s. Using Kirchhoff's voltage law the voltage relationship is:

$$Vs - L\frac{d}{dt}i - Vdc = 0 \quad (2.2)$$

The inductor voltage is V_s – V_{dc} and inductor current decreases. Therefore, in this case the inductor is in discharging state. In this case load voltage is less than zero ($V_L<0$).

Considering the negative half cycle of the ac grid voltage source i.e. when Vs<0, the switching of switches is as status C and status D in Table 1. In status C switch S_1 is turned on and inductor current path is V_s – L – S_1 – D_{S3} – V_s and in status D switch S_2 is turned on and inductor current path is V_s – L – D_{S4} – S_2 – V_S. Using Kirchhoff's voltage law the voltage relationship is:

$$Vs - L\frac{d}{dt}i = 0 \quad (2.3)$$

While $V_s<0$, in both status (status C and status D) the inductor current is decreasing and the voltage across the inductor is V_s. Therefore in both this conditions (status C and status D) the inductor current is discharging state. In both this cases load voltage is less than zero ($V_L<0$).

In negative half cycle when all switches are turned off that is when the converter is in status E. In this status as all switches are turned off the inductor current takes the path of V_s – L – D_{S4} – C – D_{S3} – V_s. Using Kirchhoff's voltage the voltage relationship is:

$$Vs - L\frac{d}{dt}i + Vdc = 0 \quad (2.4)$$

The inductor voltage is V_s+ V_{dc}, and the inductor current increase. Therefore, in the case the inductor is in charging state. In this case load voltage is greater than zero ($V_L>0$).

As a summary, in positive half cycle of ac grid voltage source $V_s>0$, both status A and status B the inductor current increases and status E the inductor current decreases to achieve ac current shaping and dc voltage regulation. While in negative half cycle of ac grid voltage $V_s<0$, both status C and status D the inductor current decreases and status E the inductor current increases to accomplish ac current shaping and dc voltage regulation. Regardless whether the ac grid voltage source is operating in the positive half cycle $V_s>0$ or negative half cycle $V_s>0$, the converter inductor current can be increased or decreased properly in the proposed PWM operation in rectifier mode.

4. Inverter Mode

The switching combination of the proposed PWM operated in the inverter mode is listed in Table 2. When the converter is operated in the inverter mode the actual inductor current is in the reverse direction compared to the ac grid voltage. In positive half cycle of ac grid voltage source i.e. when $V_s>0$, the switching of switches is as status F and status G as listed in Table 2. The input current is in the reverse direction $i_L<0$. In status F switch S_1 is turned on and inductor current path is V_s – L – S_1 – D_{S3} – V_s and in status G switch S_2 is turned on and inductor current path is V_s – L – D_{S4} – S_{S2} – V_s. Using Kirchhoff's voltage law, the voltage relationship is:

$$Vs - L\frac{d}{dt}i = 0 \quad (2.5)$$

In both this conditions (status F and status G) the inductor current is in charging state. In both this cases load voltage is greater than zero ($V_L>0$).

In positive half cycle when S_1 and S_2 switches are turned on that is when the converter is in status H. In this status the inductor current takes the path of $V_s - L - C - S_1 -$ Load $- S_2 - V_s$. Using Kirchhoff's voltage law, the voltage relationship is:

$$Vs - L\frac{d}{dt}i - Vdc = 0 \quad (2.6)$$

The inductor has negative voltage and inductor current is in discharging state. In this condition load voltage is less than zero (V_L<0).

Considering the negative half cycle of the ac grid voltage source i.e. when V_s<0, the input current is in reverse direction i_L>0. The switching of switches is as status I and status J in Table 2. In status I switch S_4 is turned on and inductor current path is $V_s - L - S_4 - D_{S2} - V_s$ and in status J switch T_{B+} is turned on and inductor current path is $V_s - L - D_{S1} - S_3 - V_s$. Using Kirchhoff's voltage law, the voltage relationship is:

$$Vs - L\frac{d}{dt}i = 0 \quad (2.7)$$

In both the status inductor voltage is negative and inductor current is in discharging state. In both this cases load voltage is less than zero (V_L<0).

In negative half cycle when S_4 and S_3 is turned on that is when converter is in status K. In this status the inductor current takes the path $V_s - L - S_4 - C - S_3 - V_s$. Using Kirchhoff's voltage law, the voltage relationship is:

$$Vs - L\frac{d}{dt}i + Vdc = 0 \quad (2.8)$$

In this case inductor voltage is positive and inductor current is in charging state. In this case load voltage is greater than zero (V_L>0).

As a summary, in positive half cycle of ac grid voltage V_s>0, both status F and status G the inductor current increases and in status H the inductor current decreases to achieve ac current shaping and dc voltage regulation. While in negative half cycle of ac grid voltage V_s<0, both status I and status J the inductor current decreases and in status K the inductor current increases to accomplish ac current shaping and dc voltage regulation. Regardless whether the ac grid voltage source is operating in the positive half cycle V_s>0 or negative half cycle V_s<0, the converter inductor current can be increased or decreased properly in the proposed PWM operation in inverter mode.

In a single phase AC/DC PWM converter the ac grid line voltage can be increased or decreased in both rectifier and inverter mode to achieve bidirectional power flow and proper line current shaping and voltage regulation in the proposed simplified PWM strategy.

5. Feed-Forward Control

The proposed feed forward control scheme applied to single phase bidirectional AC/DC converter is shown in Fig 3.1

The proposed feed forward control scheme is obtained by added duty ratio feed forward control for the dual loop control system. For a convenient explanation the converter operated in the rectifier mode is considered first. The rectifier mode switching combination is listed in Table 1. One can choose operation status A and status E during the condition V_s >0, status C and status E during V_s <0. It should be noted that selection of status A or status B can be selected for increasing inductor current, and status C or status D can be selected for decreasing inductor current.

To drive the state-space averaged equation for the proposed PWM strategy the duty ratio D_{on} is defined as $D_{on} = t_{on}/T$, where t_{on} is the time duration when switch is turned ON, ie. S_{on} =1, and T is the time period of the triangular waveform. The duty ratio D_{off} is defined as D_{off} =1-D_{on}, which is the duty ratio when the switch is turned off.

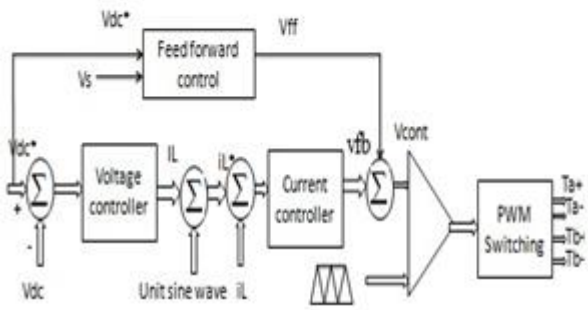

Figure 3.1: The proposed control scheme for the proposed PWM strategy

While the ac grid voltage source is operating in the positive half cycle V_s>0, the switching duty ratio of status A is defined as D_{on} and that of status E is defined as D_{off}. By introducing the state space averaged technique and volt-second balance theory the state space averaged equation is derived as follows

$$Vs - (1-D_{on})\, V_{dc}=0$$

When converter is operated in the steady state, the DC voltage is equal to the desired command $V_{dc}=V_{dc}^*$, above equation can be expressed in the following form

$$D_{on} = (1-Vs/V_{dc}^*)$$

While the ac grid voltage source is operating in the negative half cycle V_s<0, the duty ratios corresponding to status E and status C are D_{on} and D_{off}, respectively. By introducing the state space averaged technique and volt-second balance theory the state space averaged equation is derived as follows

$$V_s + D_{on}\, V_{dc}=0$$

Similarly while the converter is operated in the steady state the output voltage is equal to the desired command $V_{dc}=V_{dc}^*$, above equation can be expressed in the form

$$D_{on} = -V_s/V_{dc}^*$$

According to the PWM properties the switching duty ratio can be expressed in the terms of the control signal and peak value of the triangular waveform.

$D_{on} = V'_{cont} / V'_{tri}$

The switching duty ratio in both conditions $V_s>0$ and $V_s<0$ are derived

$$V'_{cont} = \begin{cases} \left(1 - \frac{Vs}{Vdc*}\right) V'tri, \text{ if } Vs > 0 \\ -\frac{Vs}{Vdc*} V'tri, \text{ if } Vs < 0 \end{cases}$$

Consider that the converter is operated in the inverter mode with the switching combination listed in Table 2. One can choose status F or status G and status H for increasing and decreasing the inductor current, respectively, during the condition $V_s>0$, and status I or status J and status K for decreasing and increasing the inductor, respectively, during the condition $V_s<0$. While converter is operated in the inverter mode, the control signal v'_{cont} can be obtained in similar manner in the rectifier mode. The control signal V'_{cont} operated in the inverter mode is as follows

$$V'_{cont} = \begin{cases} \left(1 - \frac{Vs}{Vdc*}\right) V'tri, \text{ if } Vs > 0 \\ -\frac{Vs}{Vdc*} V'tri, \text{ if } Vs < 0 \end{cases}$$

Because the controls signal v'_{cont} is proportional to D_{on} .The control signal V'_{cont} can be obtained by adding the duty ratio feed forward control signal V_{ff} to the dual loop feedback control signal V_{fb}. The feed forward control single V_{ff} can enhance the control ability to provide fast output voltage response as well as improve current shaping.

6. Simulation Circuits

To verify the validity of the proposed simplified PWM strategy and the feed-forward control scheme, the well-known software MATLAB 2013a was adopted to carry out the simulation process. The complete simulation can be divided into three parts namely basic circuit, feed forward control and gate signal control as shown in figure 4.1, 4.2 and 4.3 respectively.

The mode from inverter to rectifier can be changed according to the availability of DER voltage.

Parameters	*Values*
Grid voltage Vin	110sinwtV
Inductance L	1.65µH
Capacitance C	1400µF
Dc voltage(for inverter mode)	300V
Load AC Load DC Load	 100Ω 1.5Ω
Switching frequency	50Hz

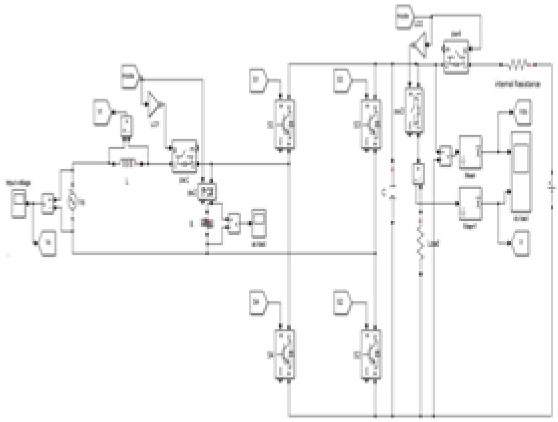

Figure 4.1: Basic circuit of the proposed circuit

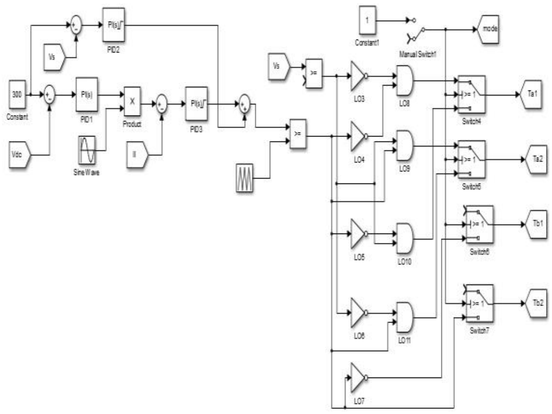

Figure 4.2: Feed forward control for proposed circuit

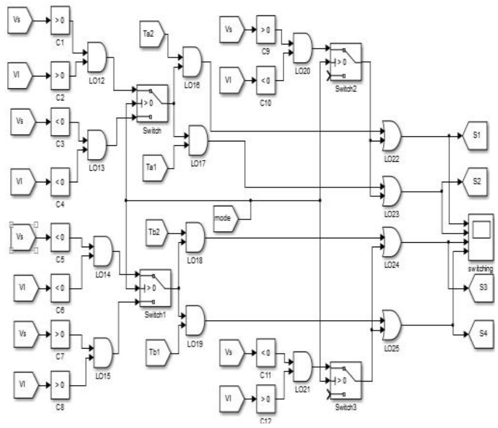

Figure 4.3: Gate signal for the proposed circuit.

7. Simulation Results

Input AC sinusoidal voltage of 110V is given to the system as grid voltage as shown in fig.5.1.

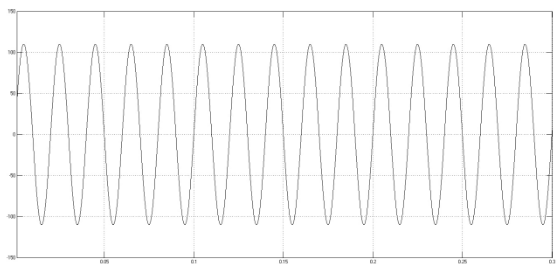

Figure 5.1: Grid voltage (AC voltage)

The circuit is operated in rectifier mode from time period 0 to 0.4s and 0.78s to 1 min in this period the ac grid voltage is converted to dc voltage of 280V as shown in fig 5.2 at this period the ac load is disconnected and is zero as shown in fig 5.3. While in the inverter mode the dc voltage of 300v is converted to ac voltage of pulses as shown in the Fig 5.3 from time period 0.4s to 0.78s.

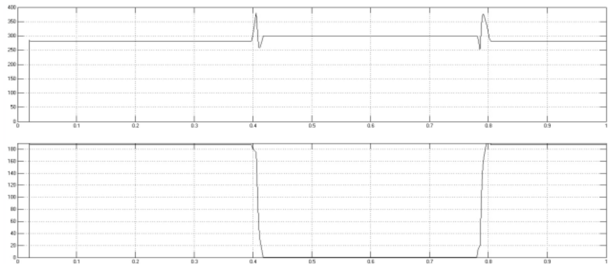

Figure 5.2: DC load voltage and current waveforms

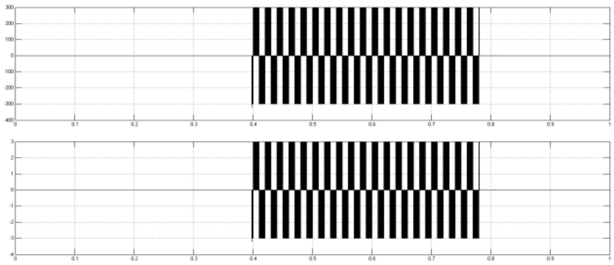

Figure 5.3: AC load voltage and current waveforms

In the Fig 5.4 we can observe that only one switch is on at a time.

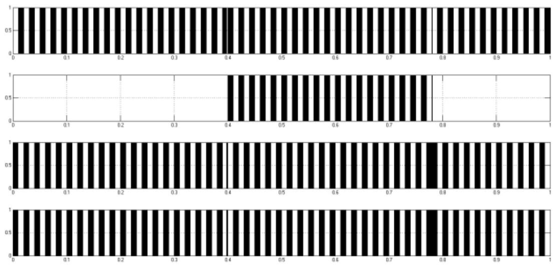

Figure 5.4: Switching sequences of IGBT switches

8. Conclusion

In this paper a novel bidirectional AC/DC converter with a feed-forward control scheme is first presented. The proposed PWM strategy requires changing of one active switch status in the switching period instead of changing four active switch statuses as required in the unipolar and bipolar PWM strategy. The efficiency of an AC/DC converter operated in the proposed simplified PWM strategy is higher than that in the unipolar and bipolar PWM strategy. Based on the proposed feed-forward control scheme both AC current shaping and DC voltage regulation are achieved in both the rectifier and inverter operating modes. In addition, the proposed simplified PWM operated in the inverter mode has larger available fundamental output voltage V_{AB} than both BPWM and UPWM. The simulation results validity of the proposed PWM strategy and control scheme.

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